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When certain types of materials, particularly ferrites, are brought near a piece of magnetite, they experience a force which is due to the presence of the magnet. In explaining this force we make use of the concept of the magnetic field. It is the magnetic field set up by the magnetite which is the cause of the force experienced by the ferrite material.

Similarly, when a small, electrically charged test particle is brought near another stationary, electrically charged particle, a force is experienced by the charged test particle. In order to explain the force, we postulate a concept analogous in many ways to the magnetic field, i.e., the electric field. It is the electric field set up by the stationary charge which causes the force experienced by the test charge.

Both of these phenomena are fairly common experiences. Two additional phenomena which relate a little less readily to everyday experience are also important. The first is that when a magnetic field varies with time, we find that it generates an electric field. The second is analogous: when an electric field varies with time, it produces a magnetic field. Thus, electric fields and magnetic fields varying together in consistent patterns are often found in nature. These fields are consequently usually treated together as two aspects of a single phenomenon: the electromagnetic field. The properties of electromagnetic fields,

consisting of the varying electric and magnetic fields just mentioned, are set forth in Maxwell's Equations, which were formulated by James Clerk Maxwell in the nineteenth century. We have since found many instances of these electromagnetic fields in nature and many applications for them.

The electromagnetic fields in which we are most interested are periodic ones, oscillating at definite characteristic frequencies and having specific wavelengths. The cycle/second is the unit of frequency and in modern terminology has come to be called a Hertz, so named for Heinrich Hertz who was an early electromagnetic experimenter. So a cycle/second is now referred to as a Hertz. Very low frequencies of oscillation, in the neighborhood of ten to ten thousand cycles/second, or Hertz, are most often used for power transmission and telephone-type transmission and have wavelengths on the order of hundreds and even thousands of miles. In the next higher frequency interval, from about ten thousand to about one billion Hertz, most radio and television transmitters operate, with wavelengths from a few miles at the lower frequencies in the band to a few feet at the higher frequencies. Beginning at about a billion Hertz and extending to about a trillion Hertz is what is known as the microwave region, and we will discuss this in some detail in a moment. Here the wavelengths run from a few feet down to a few hundredths of an inch. On a logarithmic plot of these familiar portions of the electromagnetic spectrum, we find the microwave region lying just below the middle. Like all other sections of the electromagnetic spectrum, the

microwave region is populated by electric and magnetic fields varying in time and propagating through space at the speed of light. The next higher frequency interval, from about a trillion Hertz to about 300 trillion Hertz, is the infrared region where surface heating is a common phenomenon, and optical methods of detection like photography begin to replace electrical ones like antennas. In the relatively narrow region from 300 trillion Hertz to one quadrillion Hertz lies the portion of the electromagnetic spectrum to which the human eye is sensitive. This is the region of visible light. Wavelengths here are measured in thousands of Angstroms. (One Angstrom is equal to approximately four one-billionths of an inch.) From about one quadrillion Hertz, which is the upper boundary of the visible region, to about 100 quadrillion Hertz lies the ultraviolet region, with wavelengths down to 10 Angstroms, or so. At frequencies higher than this we find X-rays, and at higher frequencies still, gamma rays with wavelengths ultimately extending down to millionths of an Angstrom.

At the very high frequencies of X- and gamma rays, varying electromagnetic fields have been found to be generated in small, discrete units or "packets," called photons. The energy carried by one of these photons has been found to depend upon the frequency of its electromagnetic oscillation. That is, a photon of specific electromagnetic frequency f can only carry a specific energy E. Conversely, if a photon carries a specific energy E, it can only be oscillating at the specific frequency f.

Since there exists this fixed relationship between photon energy and frequency, and since the frequencies of oscillation of X- and gamma rays are obviously so cumbersomely large, in this range photon energy, expressed in units of electron-Volts, is the normal mode of classification rather than frequency. X- and gamma rays have photon energies running from about one thousand electron-Volts to 10 billion electron-Volts and beyond. This region of the electromagnetic spectrum is generally referred to as ionizing radiation because each photon carries approximately enough energy to break up a molecule into component parts called ions. By contrast, the photon energy of a microwave photon is only a few ten-thousandths of an electron-Volt, which is not sufficient to break up molecules into ions in the manner of ionizing radiation photons. Of particular interest to us is the corollary that the biological significance and the potential hazards associated with ionizing or nuclear radiation are, in general, different from those associated with microwave radiation.

The primary means of interaction of microwave radiation with biological systems, for example the human body, seems to be via tissue heating. Roughly speaking, this tissue heating takes place in the following way. The body is composed of molecules, many of which have an uneven distribution of electrical charge within themselves, although their total electrical charge is zero with positive and negative charges balancing out within the molecule. A force is exerted on these molecules due to the presence of the electrical field component of the microwave radiation.

These polar molecules then try to align themselves with the field as it oscillates, and so end up moving back and forth rapidly. This motion of the molecules may then be transmitted to adjacent molecules through collision, and the resulting increased motion of all of these molecules corresponds to an additional kinetic energy of the molecules and is experienced on a macroscopic scale as a rise in temperature. The current exposure standards throughout the Western World are based on the assumption that this thermal interaction with biological systems is the only important type of interaction.

The accepted biological damage resultant from excessive exposure to microwave radiation is, in general, the damage induced by hyperthermia, or excessive body temperature. Exposure level is usually specified in power (usually in units of milliwatts) incident upon a given area (usually in units of square centimeters) and so is described as power density and given in units of milliwatts/square centimeter. According to Schwan and Pierson the field strength which corresponds to the level of the body's heat dissipation abilities is 10 mW/cm^2, although under very favorable circumstances it is possible for this maximum level of heat dissipation to rise tenfold. Hence, under normal circumstances, for whole-body exposure levels greater than 10 mW/cm^2 the rate of energy input to the body is more than the body can dissipate and there is some heat build-up in the body and a concomitant rise in body temperature. According to Ely and Goldman, a continuous whole-body exposure of 100 mW/cm^2 would result in a maintained increase in body temperature of slightly more than 3 1/2° F.

Experimental evidence has established that certain organs (the eyes, testicles, gall bladder, urinary bladder, and portions of the gastrointestinal tract) are more susceptible than others to microwave radiation. These are, in general, those organs one would expect to find affected by hyperthermia. The eyes and the testicles, organs having high thermal sensitivities, seem to be the most sensitive to microwave radiation. The prime damage to the eye seems to be cataract formation due to heat buildup in the lens. This has been shown to occur at power density levels on the order of hundreds of mW/cm^2. Damage to the testes usually is in the form of a reduction of spermatocytes and damage to the cells lining the seminiferous tubules. The minimum field strength capable of producing the smallest notable testicular result in experimental animals has been found to be about 10 mW/cm^2. It should be stressed, however, that the damage observed at such low levels was slight, almost fully recoverable, and in no way different from that due to other common forms of heat that might be applied to the testes.

The existence of effects resulting from nonthermal interactions, i.e., modes of significant biological interaction in which negligible amounts of tissue heating are involved, has been postulated. Suggested nonthermal effects include neurological interaction effects, genetic effects, and others. The existence and significance of such nonthermal effects are controversial matters at present, but are the apparent basis for the exposure standards promulgated in many of the eastern countries.

Having now examined some of the basic physical properties and biological hazards of microwave radiation, let us turn to an examination of

the common applications of this radiation to find what the potential sources of public exposure may be. As previously mentioned, the microwave spectrum covers the frequency interval from about one billion Hz (which is one thousand Megahertz) to about one trillion Hz (one million MHz). In reality, however, almost no use is made of the upper 90% of this region because of extreme technical difficulties encountered at these high frequencies. In fact, almost all common applications of microwave energy fall in the bottom 1% of the microwave interval, i.e., the region around 1,000 to 10,000 MHz.

One of the most common applications of microwave radiation is in radar. A radar releases very short and very powerful pulses of microwave radiation in a tightly focused beam. After transmission from the radar, the pulse strikes the target and is reflected back to the radar where it is picked up by the radar antenna. By measuring the time between the initial transmission of the pulse and the reception of the reflected pulse, the distance from the radar to the target can be computed. Microwave energy is used for this application rather than lower frequency radio waves because it is possible to focus the microwave energy into a much narrower beam, which is very desirable in the determination of target location.

Another common application of microwave energy, which results largely from the narrow beamwidth possible at microwave frequencies, is the growing network of microwave communications links. Usually these are low power,

point-to-point communication systems. They are becoming increasingly popular for reasons of reliability and maintenance economy, as well as higher information transfer rates.

For noncommunications uses the Federal Communications Commission has allocated several industrial-scientific-medical frequency bands, or ISM bands. One type of process taking place in the ISM bands is industrial drying using microwave radiation. The principle of interaction in this application is identical with the thermal interaction with biological systems previously discussed. The heating property is used to dry everything from plywood to potato chips, and the power density levels are normally quite high.

The application in which you will be most interested is one very similar to industrial drying, and one which also takes place in the ISM bands. This application is that of cooking food in microwave ovens. Microwave ovens operate in two of the ISM bands: one around 915 MHz and one around 2450 MHz (most ovens operate in the latter).

A typical microwave oven consists of (1) a microwave tube, generating on the order of 1,000 Watts, (2) a rectangular metal guide which directs the microwave energy from the generating tube to the oven cavity, (3) a rotating fan-type stirrer which continually alters the direction of the microwave radiation going into the oven cavity to produce an even irradiation of the surface of the food being prepared, and (4) the oven cavity itself.

The biggest advantage of the microwave oven over the conventional type seems to be the very short cooking times required in the former. For example, it would take about five hours to cook a 14-pound turkey in a conventional oven, whereas it could be prepared in a microwave oven in one hour and 15 minutes. Two basic phenomena account for this speed: (1) in a conventional oven the air in the cavity must first be heated before efficient heat transfer can begin, whereas microwave radiation has very little interaction with the oven air and goes immediately to the surface of the food, and (2) in a conventional oven most of the energy is deposited at the surface of the food and time is required for conduction to the inner sections of the food, whereas microwave radiation penetrates more deeply into the food being prepared and so cooks the food throughout simultaneously.

The principal factor which concerns us with microwave ovens is the possibility that microwave energy may escape from the oven at levels which present a potential biological hazard. In general, this can happen in two ways. (1) Although all ovens have interlock mechanisms designed to cut off the microwave generating tube if the door is opened while the oven is in operation, these interlocks may fail or be intentionally defeated by personnel unfamiliar with the hazards associated with excessive microwave radiation exposure. (2) Even if the interlocks are in perfect working order, wear around the door seals can result in gaps in the seal between the door and the oven frame which permit the leakage of potentially hazardous levels of microwave radiation.

There are several types of instruments available for use in measuring the leakage levels emanating from a microwave oven. Aside from the varying levels of measurement accuracy and the varying maximum and minimum measurable levels inherent in the different types of instruments, there are at least two technical problems involved in the surveying of microwave ovens which are worth noting briefly.

The first is the near field problem. Simply stated, the near field problem results from the fact that the introduction of the measuring instrument into the leakage field very close to the oven causes some distortion in the leakage field. The distortions caused by the measuring instrument were not present before the introduction of the instrument and will not be there after the instrument is removed. But since the instrument is itself obviously present while close measurements are being made, the distortion is there while the measurement is being made. This means that at close range the relationship of the measured field to the actual field after the removal of the measuring device may be very complex, and for some situations is unknown. This problem is particularly marked in large probes which incorporate a substantial amount of metal. The problem is true of smaller probes but to a lesser extent and at a lesser distance from the oven.

The second problem is the polarization problem. The polarization of an electromagnetic field is the orientation of the electric field component of the field. This electric field may always lie in a straight line

(in which case it is called a linearly polarized field) or it may move and rotate about. Some types of survey instruments have responses that are highly polarization-sensitive, and must be aligned in a certain way relative to the leakage field in order to obtain a true reading.

In each of these problems, the limitations of the device being used to measure the oven leakage must be clearly understood by the user in order to avoid erroneous measurements.

The last subject we will touch on is that of standards. The exposure standard throughout most of the Western World is 10 mW/cm^2, either constantly or averaged over some time period. As previously mentioned, this is based on the principle of thermal interaction of microwave radiation with the human body.

The continuous exposure standards currently promulgated in a number of eastern countries is 10 microwatts/cm^2--lower than the western standards by a factor of 1,000. As previously mentioned, this is presumed to be based on a nonthermal interaction model.

In addition to these exposure standards, there exist certain performance standards for microwave ovens. Currently these are voluntary industrial standards, as there is as yet no official U. S. Public Health Service standard. The voluntary performance standard set by industry limits the permissible microwave oven leakage to a maximum of 10 mW/cm^2. It is noteworthy, however, that in a recent compilation of the results of surveys on 494 ovens, 109 ovens (approximately 22%) were found to be

leaking in excess of 10 mW/cm^2, and some were leaking as much as 200 mW/cm^2. There has been a new standard proposed by a U. S. Public Health Service advisory committee which would limit permissible oven leakage to 1 mW/cm^2 at the time of manufacture, and 5 mW/cm^2 over the life of the oven. As yet, however, this recommendation has not been acted upon.

In conclusion, while recognizing the compelling advantages of microwave radiation in many applications, we would seem to be well advised to take measures to ensure the safety of those involved in the processes where microwave energy is utilized.

REFERENCES

(1) Rosenstein, Marvin, Warren A. Brill, and Charles K. Showalter: Radiation Exposure Overview--Microwave Ovens and the Public. U. S. Department of Health, Education, and Welfare, Public Health Service, Bureau of Radiological Health, OCS-69-1 (July 1969)

(2) Moore, Wellington, Jr.: Biological Aspects of Microwave Radiation--A Review of Hazards. U. S. Department of Health, Education, and Welfare, Public Health Service, Bureau of Radiological Health, TSB-68-4 (July 1968).

(3) Schwan, H. P., and G. M. Piersol: The Absorption of Electromagnetic Energy in Body Tissues. A Review and Critical Analysis. Part II, Physiologic and Clinical Aspects. Amer. J. Phys. Med., 34: 423-448 (1955).

(4) Ely, T. S., and D. E. Goldman: Heating Characteristics of Laboratory Animals Exposed to Ten-Centimeter Microwaves. In: Proceedings of Tri-Service Conference on Biological Hazards of Microwave Radiation. ARDC-TR-58-51. E. G. Pattishall, ed. University of Virginia, 1957, pp. 64-75.